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1.2.2008

Lithium Abundance of Halo Dwarfs Revised

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Accepted: January 1995

Abstract. Lithium abundances in a sample of halo dwarfs have been redetermined by using the new T_{eff} derived by Fuhrmann et al (1994) from modelling of the Balmer lines. These T_{eff} are reddening independent, homogeneous and of higher quality than those based on broad band photometry. Abundances have been derived by generating new atmospheric models by using the ATLAS-9 code by Kurucz (1993) with enhanced α-elements and without the overshooting option. The revised abundances show a remarkably flat *plateau* in the Li-T_{eff} plane for $T_{eff} > 5700$ K with no evidence of trend with T_{eff} or falloff at the hottest edge. Li abundances are not correlated with metallicity for [Fe/H]< -1.4 in contrast with Thorburn (1994). All the determinations are consistent with the same pristine lithium abundance and the errors estimated for individual stars fully account for the observed dispersion. The weighted average Li value for the 24 stars of the plateau with $T_{eff} > 5700$ K and [Fe/H]$\leq$ -1.4, is [Li] = 2.210 $\pm$ 0.013, or 2.224 when non-LTE corrections by Carlsson et al (1994) are considered.

Key words: Stars: abundances – Stars: Population II – Stars: fundamental parameters – Galaxy: halo – Cosmology: observations

1. Introduction

The lithium observed in the atmospheres of unevolved halo stars is generally believed to be an essentially unprocessed element which reflects the primordial yields. In the framework of the standard BBN it provides a sensitive measure of $\eta = n_b/n_\gamma$ at the epoch of the primordial nucleosynthesis and thus of the present baryon density Ω_b. The primordial nature of the lithium of the halo dwarfs is inferred from the presence of a constant lithium abundance for all the halo dwarfs where convection is not effective ($T_{eff} \geq 5600$ K). Such an uniformity is taken as evidence for the absence of any stellar depletion during the formation and the long life of the halo stars and also as evidence for the absence of any production mechanism acting either before or at the same time of the formation of the halo population.

The existence of a real *plateau* has been recently questioned by Thorburn (1994), Norris et al (1994) and Deliyannis et al (1993). Thorburn (1994) found trends of the Li abundance both with T_{eff} and [Fe/H], while Norris et al (1994) found that the most extreme metal poor stars provide lower abundances by $\approx$ 0.15 dex, thus questioning their genuine primordial value. An intrinsic dispersion of Li abundances in the plateau was claimed by Deliyannis et al (1993) from the analysis of the *observable* EW and $(b\text{-}y)_0$. These results open the possibility of substantial depletion by rotational mixing where a certain degree of dispersion is foreseen for different initial angular momenta of the stars and/or to a significant Galactic lithium enrichment within the first few Gyrs. Thus it appears rather problematic to pick up the precise primordial value from the observations of the Pop II stars. Thorburn (1994) has suggested to estimate it from the surface lithium abundances of the hottest and most metal-poor stars.

In this work we tackle these problems by recomputing the lithium abundances for a significant subset of those stars already studied in literature for which new and better effective temperatures are now available. A possible origin of the systematic differences in the lithium abundances resulting in the most recent determinations will also be discussed. Further details can be found in Molaro et al (1995).

2. Lithium Abundances

2.1. The role of T_{eff} and of atmospheric models

In the atmospheres of G dwarfs lithium is mainly ionized and the abundance determination is particularly sensitive to the effective temperature and to the $T(\tau)$ behaviour inside the photosphere since it requires large ionization corrections. Conversely, lithium abundance is not particularly sensitive to the stellar surface gravity and to the metallicity of the star. Also the LiI 6707 Å line is not generally saturated due to the intrinsically low lithium abundance of the halo stars, and therefore it is insensitive to the value of the microturbulent velocity. The effective temperature is by far the most important parameter and its accuracy determines the ultimate lithium abundance accuracy. Unfortunately, the determination of the effective temperature for cool stars and in particular for metal poor stars is rather poor, as discussed in detail in Fuhrmann et al (1994). Fuhrmann et al pointed out the severe limitations of the methods based on broad band photometry, which they considered inadequate to provide accurate effective temperatures for

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individual stars. The main arguments rely on the dependence of colour-based temperatures on the reddening corrections and on the particular color used.

Table 1. Table 1

Star	$T_B \pm \sigma_{T_B}$	$\log g$	EW$\pm\sigma_{EW}$	[Li]$\pm\sigma_{Li}$
HD 3567	5750±200	4.0	45±5.8	2.221±0.197
HD 19445	6040±52	4.2	33.6±0.5	2.253±0.039
HD 64090	5499±56	4.1	12.1±0.7	1.331±0.062
HD 74000	6211±44	4.5	25±3.2	2.215±0.073
HD 108177	6090±77	4.3	30±1.3	2.229±0.063
HD 116064	5822±72	3.6	30±2.5	2.015±0.073
HD 140283	5814±44	3.6	46.5±0.6	2.262±0.036
HD 160617	5664±84	3.5	42±3.8	2.103±0.087
HD 166913	5955±109	3.3	40±3.8	2.294±0.100
HD 188510	5500±220	4.0	18±3.4	1.516±0.222
HD 189558	5573±92	4.0	42±1.6	2.021±0.086
HD 193901	5700±109	4.0	30±3.3	1.962±0.111
HD 194598	5950±100	4.0	27±0.7	2.094±0.076
HD 200654	5522±119	3.2	8±1.7	1.129±0.143
HD 201889	5645±61	4.1	5±3.3	$1.065^{+0.230}_{-0.500}$
HD 201891	5797±57	4.4	24.3±0.8	1.925±0.048
HD 211998	5338±65	3.5	13±3.4	1.219±0.150
HD 219617	5815±76	4.2	40.2±0.8	2.198±0.062
BD 2° 3375	6034±60	4.0	31.5±2.1	2.198±0.058
BD 3° 740	6264±73	3.5	17.3±1.3	2.062±0.065
BD 9° 352	6285±77	4.5	34±6.7	2.429±0.130
BD 9° 2190	6452±60	4.0	18±3.4	2.200±0.107
BD 17° 4708	6100±110	4.1	25±1.7	2.139±0.084
BD 21° 607	6135±70	4.0	25±2.6	2.190±0.074
BD 23° 3130	5190±84	2.7	13±1.3	1.066±0.095
BD 24° 1676	6278±76	3.9	27±1.6	2.296±0.062
BD 26° 2606	6161±64	4.1	30±1.2	2.252±0.050
BD 29° 366	5760±64	3.8	14±2.9	1.641±0.105
BD 37° 1458	5451±59	3.5	11±2.1	1.226±0.107
BD 38° 4955	5337±73	4.5	8±3.3	1.016±0.250
BD 42° 3607	5836±66	4.4	47±4.5	2.298±0.083
BD 66° 268	5511±91	4.0	10±7.8	1.237±0.476
G 64-12	6356±75	3.9	25.8±2.4	2.318±0.074
G 64-37	6364±75	4.1	14±1.2	2.029±0.066
G 66-9	5885±83	4.6	29±2.9	2.047±0.081
G 206-34	6258±50	4.3	27±2.5	2.265±0.060
G 239-12	6260±70	4.1	24±3.1	2.214±0.083
G 255-32	5962±53	4.0	30±2.9	2.119±0.064
LP 608 62	6435±52	4.1	21.5±2.3	2.282±0.063

Fuhrmann et al (1994) derived T_{eff} from the full spectral synthesis of the Balmer lines for a large sample of stars. These T_{eff} are reddening independent and they show a high degree of internal consistency when the various members of the serie are used. Being obtained from absorption lines, they are particularly suitable for line abundance applications. Fuhrmann et al are also able to provide errors in the T_{eff} for individual stars and in most cases they are as good as $\pm$ 50 K, which is a factor 2 smaller than the grossly estimated errors for photometric-based T_{eff}.

Out of the Fuhrmann et al' sample, 39 have already been studied for lithium. They represent a significant fraction of the presently available lithium determinations, and form an unique sample with a good and homogeneous T_{eff}.

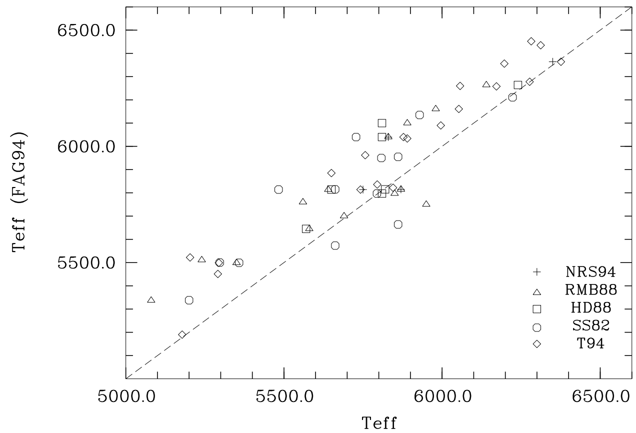

Fig. 1. T_{eff} from Fuhrmann et al (1994) versus T_{eff} from Li literature.

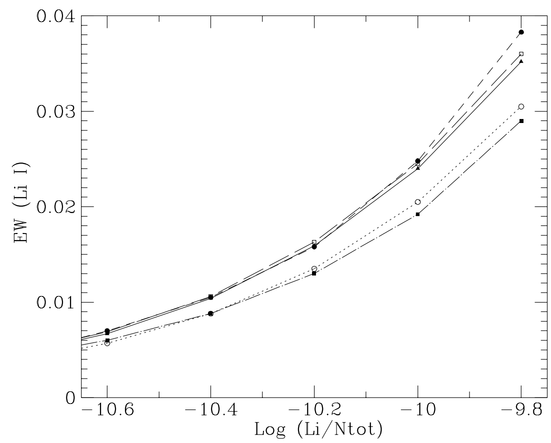

Fig. 2. Curves of Growth for different models. Dash: Bell; solid line: ATLAS8; dot: ATLAS9; Long dash: ATLAS9 without overshooting; dot - long dash: Kurucz 1991 adopted by Thorburn 1994.

On average, the Fuhrmann et al temperatures are 125±120 K higher than those previously used in literature on lithium (cfr Fig. 1). The presence of considerable scatter together with a systematic offset suggest that there are intrinsic differences in the individual temperatures derived by various methods. The Li equivalent widths have been taken from the literature and the theoretically derived random errors from Deliyannis et al (1993) or computed following their prescriptions. In the case of multiple measurements of the lithium line of the same star we adopted the weighted average to minimize the errors. Atmospheric models may be important for the lithium abundance. The role played by different atmospheric models is illustrated in Fig. 2 where several curves of growth obtained with different atmospheric models are shown. The COGs are for T_{eff} = 6000 K, logg = 3.5, microturbulence ξ = 2 km s^{-1} and [Fe/H]=-3.0,

but a similar behaviour is shown by other temperatures relevant for Li. The curves of growth for lithium obtained by using ATLAS-9 and ATLAS-8 are notably different. In Fig. 2 are also shown the COG used by Thorburn (1994) referred to unpublished models of Kurucz (1991) and to those of Bell and Gustaffsson. For a given EW the abundances of the most recent Kurucz codes are ≈ 0.1 dex higher than all the other curves. We have computed a grid of atmospheric models where the convection is treated with the mixing length theory but without the overshooting option. The corresponding COG, also shown in Fig. 2, is very close to the COG of the old Kurucz or Bell and Gustaffsson models. This shows that the implementation of the approximate treatment for overshooting in the ATLAS-9 code is likely to be responsible for the difference among the versions of the ATLAS code. The center of the convective bubbles stops at the top of the convective zone so that convective flux extends one bubble radius above the end of the convection zone. Overshooting rises the temperature in correspondence of the depths relevant for the formation of the lithium line, thus resulting in higher abundance for the same equivalent width. The effect is almost negligible at solar metallicities but it increases towards lower metallicities where the fraction of the total flux transported via convection increases.

The presence of abundances derived with different atmospheric models is also responsible for the systematic differences in the lithium abundances for common stars among different authors. This factor has been essentially overlooked and has introduced a spurious scatter in a straightforward compilation of the literature data. The comparison of the measurements of Thorburn (1994) with those of the literature shows that the equivalent widths are almost the same but the Thorburn abundances derived using Kurucz (1991) are systematically higher than those by other authors. The finding by Norris et al (1994) showing that Li abundances in stars with [Fe/H]<-3.0 are on average about 0.15 dex lower than the higher metallicity halo stars from Thorburn (1994) can be also understood as a model effect. Norris computed the Li abundances by using Bell and Gustaffsson atmospheric models which give abundances lower than those by Thorburn (1994). The comparison between the stars studied by both Norris et al (1994) and Thorburn (1994) shows nearly identical EWs for both, but lower abundances in the former authors.

Implementation of overshooting improves the reproduction of the solar spectrum, but the effects on metal poor stars have not been yet fully tested and it should be considered with caution until a deeper analysis of possible secondary effects on metal poor objects is carried out. Here we have not used this option and the new lithium abundances have been determined by computing Kurucz (1993) atmospheric models without overshooting. For all the stars the models have been computed with the temperatures available from Fuhrmann et al (1994). The gravities used are taken from the literature according to the compilation of Deliyannis et al (1993) or computed from c_0 colors, and are reported in Table 1. Convection is treated with the mixing length theory with a scale height over pressure scale of 1.25. The choice of this parameter is not critical and a change from 0.5 to 2 produces almost negligible effects on the lithium abundance. If we use the Kurucz 1993 grid which includes overshooting the lithium abundance is increased by ≈ 0.09 dex, but all other conclusions are still valid, since they are not dependent on this assumption. In view of the important implications related to the primordial abundances, it is desirable that a deeper discussion may follow shortly.

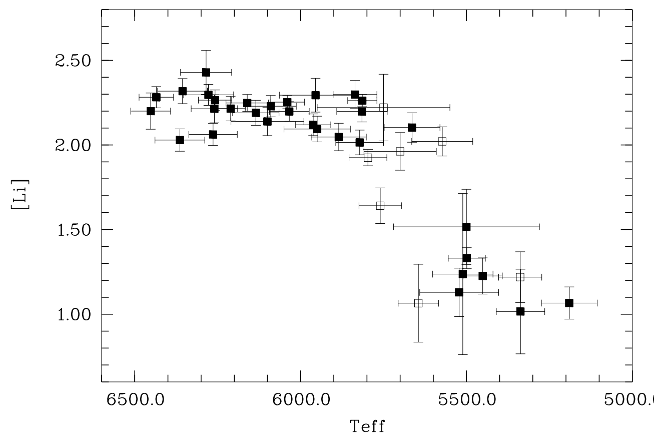

Fig. 3. [Li] versus T_{eff}. Open squares are for stars with metallicities in the range -1.4<[Fe/H]<-1.0.

3. Results

The Li abundances in the Li-T_{eff} plane with associate 1 σ errors are shown in Fig. 3. Following Rebolo et al (1988) and Deliyannis et al (1990), stars with -1.4<[Fe/H]<-1.0 (open squares in Fig. 3) are taken off from sample of genuine halo stars since they may show some depletion. The errors shown in Fig. 3 are those given in the last column of Table 1. They have been estimated by summing under quadrature the errors in the lithium abundance produced by the uncertainties in T_{eff} and in EW, also given in Table 1, namely $\sigma^2_{Li} = \sigma^2_{Li}(EW) + \sigma^2_{Li}(T_{eff})$. We have considered negligible the effects produced by uncertainties in gravity, microturbulence and metallicity. The lithium abundances show a plateau extending up to nearly 6500 K, with no evidence of falloff at the hottest edge as expected by microscopic diffusion models, and with the depletion region bending at $T_{eff} \approx 5700$ in good agreement with what observed in the Hyades.

The existence of a tilt of the plateau has received considerable attention (Molaro 1987, Rebolo et al 1988, Thorburn 1994, Norris et al 1994) since the presence of a moderate stellar depletion in the cool edge *plateau* implies that only the highest values are close to the pristine value. Norris et al (1994) and Thorburn (1994) found a slope of 0.03 and 0.024 for 100 K, respectively. Thorburn (1994) claimed also that when this underlying trend with T_{eff} is taken into account the increase of N(Li) with the metallicity becomes notable already at [Fe/H]$\approx$-2.0. Considering only stars with Teff > 5700 K and [Fe/H]$\leq$ -1.4 the weighted linear fit is [Li]$\propto 0.58(\pm 0.88)\cdot(T_{eff}/10^4)$. The slope we found is one order of magnitude lower than those of Norris et al (1994) or Thorburn (1994), and is consistent with a real *plateau* in the undepleted region of the Li-T_{eff} plane. Non-LTE effects have been studied by Carlsson et al (1994), who provide corrections of 0.020, 0.015 and 0.010 at 5500, 6000 and 6500 K respectively, and for [Fe/H] between -1.0 and -3.0. Once we correct our abundances for nonLTE effects the slope of the fit becomes even smaller: $0.29(\pm 0.93)$.

The lithium abundances versus the stellar metallicity are shown in Fig. 4 and do not show any clear trend with iron

over two orders of magnitude of increase in the stellar metallicity. Strictly speaking we observe a decrease in the lithium abundance with the increasing of the metallicity. The weighted regression analysis gives a negative slope with lithium decreasing by 0.008 dex for Δ[Fe/H]=1. By contrast Thorburn (1994) found an increase in Li by 0.4 dex from the [Li]=2.20 at [Fe/H]=-3.5 up to 2.60 at [Fe/H]=-1.0. Our interception at [Fe/H]=-3.5 is of [Li]=2.215, fully consistent with the value of [Li]=2.221 obtained from the hottest halo dwarfs (T_{eff}=6400 K). In our data sample both the lowest metallicity stars, i.e. the oldest, and the hottest subdwarf, i.e. the less depleted, share the same Li abundance.

Fig. 5 shows a zoom of the plateau region with the errors in the Li abundances at the 3 σ level plotted for each star. On the plateau all the Li abundances are consistent with a unique pristine Li abundance. In 10 out of 24 cases the consistency is achieved already at 1 σ confidence level. For three stars (G 64-13, BD 3° 740, HD 116064) the full 3σ error box is required to achieve the consistency, and they might show a real dispersion if errors can be further reduced. With the present estimated errors our analysis does not support the presence of real dispersion on the plateau region, and it seems likely that the dispersion claimed by Thorburn (1994), or the correlations of Li with metallicity or temperature, are artifacts caused by errors in the effective temperatures. We stress that both the absence of a tilt and dispersion in the plateau region are independent of the assumption we made on overshooting, since its inclusion would increase the Li abundance by about the same amount for all the stars. The weighted mean on the plateau of the 24 stars with $T_{eff} \geq 5700$ and [Fe/H]$\leq$ -1.4, where each abundance is weighted inversely by its own variance in the sum, is [Li]=2.210 $\pm$ 0.013. When the non-LTE corrections of Carlsson et al (1994) are considered, the mean rises to 2.224 $\pm$ 0.013. This value is somewhat higher than the 2.08$\pm$0.1 previously estimated by Spite and Spite (1982), Hobbs and Duncan (1988), Rebolo et al (1988), and Molaro (1991). The increase in the value of the plateau results from the increase of the Fuhrmann et al effective temperatures compared to those previously used in the lithium literature.

The present analysis shows that when very precise effective temperatures and individual errors are considered, the Li abundances on the plateau show no trends either with T_{eff} in a range of 600 K or with the stellar metallicity over two orders of magnitude. The lithium abundances are all closely gathered and are consistent with the same initial abundance, thus confirming that the lithium observed in these stars is essentially undepleted and very close to the primordial value as already put forward by Spite and Spite (1982).

Acknowledgements. It is a pleasure to thank Fiorella Castelli and Bob Kurucz for many useful discussions in particular on the role played by atmospheric models on the lithium abundance. Partial support from a bilateral CNR grant is acknowledged.

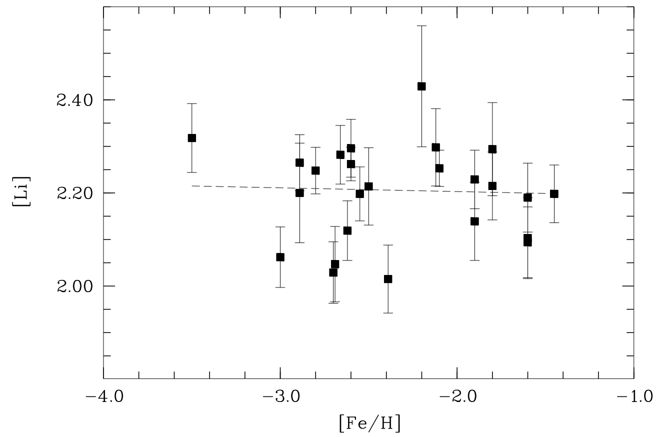

Fig. 4. Li-[Fe/H].

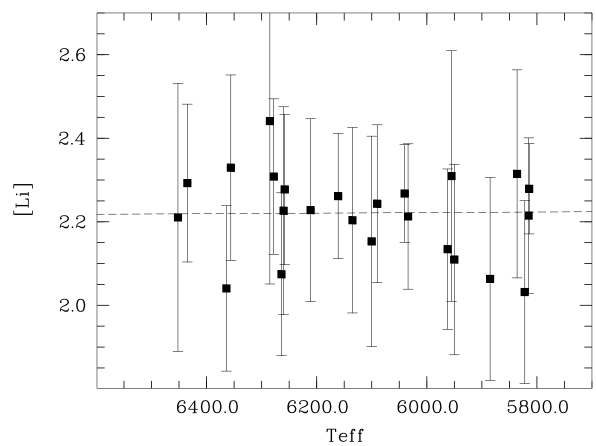

Fig. 5. Zoom on the *plateau*, with the [Li] abundances corrected for non-LTE effects. The errors are at 3 σ. The dash line shows the weighted mean at [Li]=2.224.

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